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(54) **METHODS AND SYSTEMS FOR MINIMIZING VIBRATION RECTIFICATION ERROR IN MAGNETIC CIRCUIT ACCELEROMETERS**

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G01P 15/13 (2006.01)

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(58) **Field of Classification Search** 73/514.31, 73/514.23, 514.17, 514.21, 514.29, 493, 73/514.36, 514.38
See application file for complete search history.

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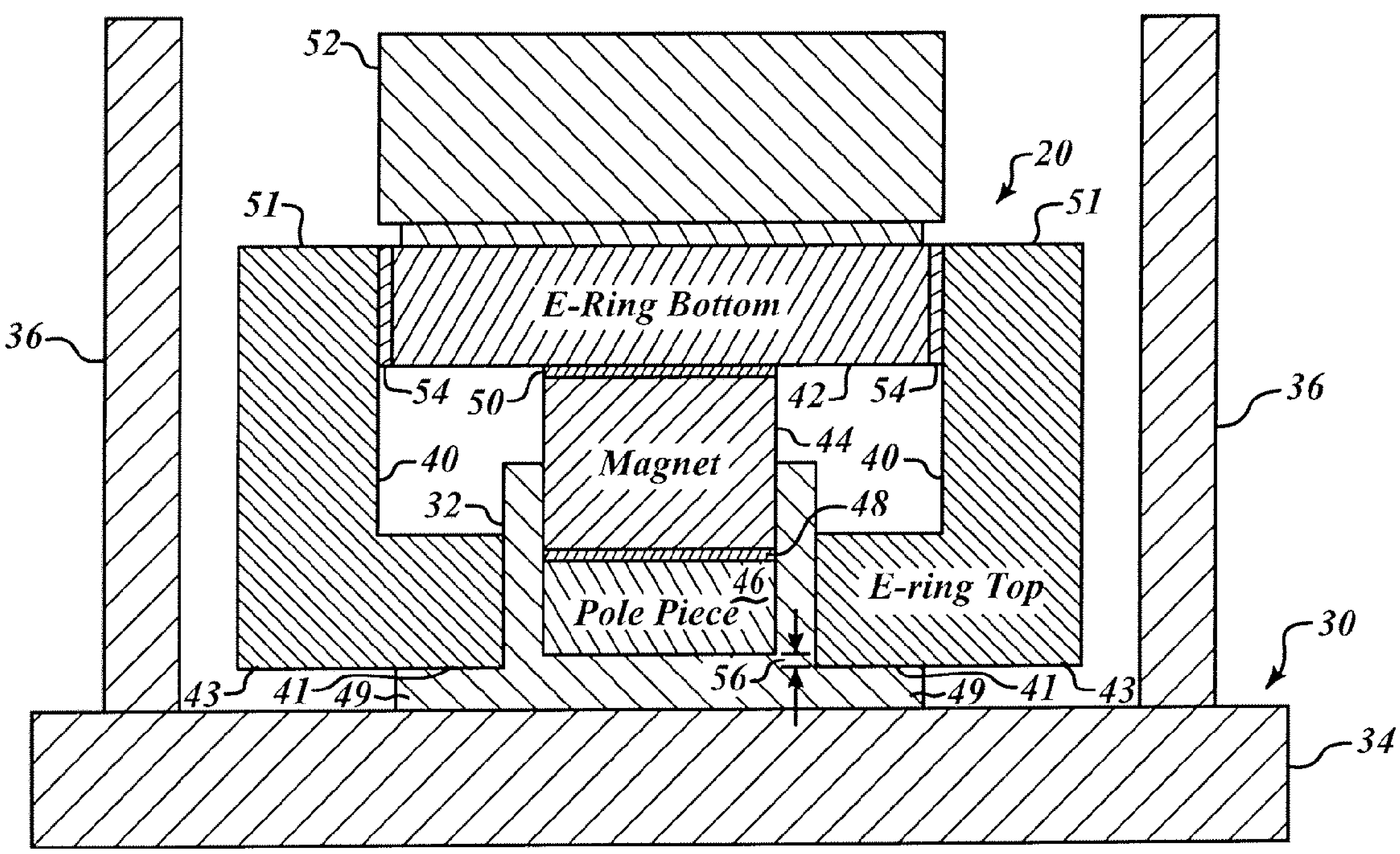
(57) **ABSTRACT**

Systems and methods for minimizing vibration rectification error in magnetic circuit accelerometers. The systems include an accelerometer with an excitation ring that has a top piece with a lower portion inner diameter and a bottom piece having a diameter smaller than the lower portion inner diameter of the top piece. The accelerometer also includes a proof mass, a magnet mounted to the bottom piece of the excitation ring, a pole piece mounted to the magnet, and a coil attached to the proof mass that extends into a gap between the top piece of the excitation ring and the pole piece. The methods include placing a pole piece in a pole piece to lap surface fixture, placing an excitation ring top piece on an outer portion of the pole piece to lap surface fixture, and placing an excitation ring bottom piece in a lower portion of the excitation ring top piece.

20 Claims, 3 Drawing Sheets



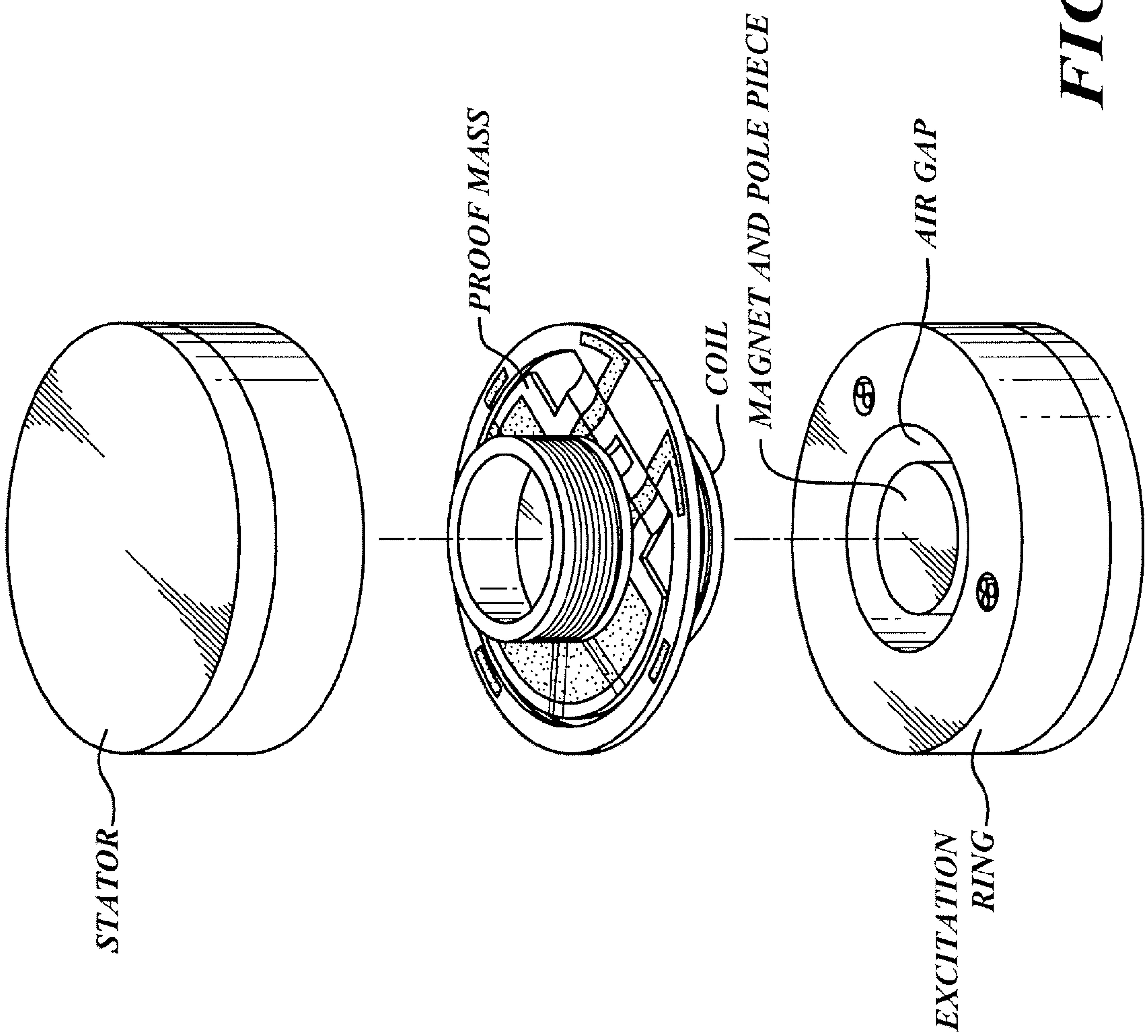


FIG. 1 (PRIOR ART)

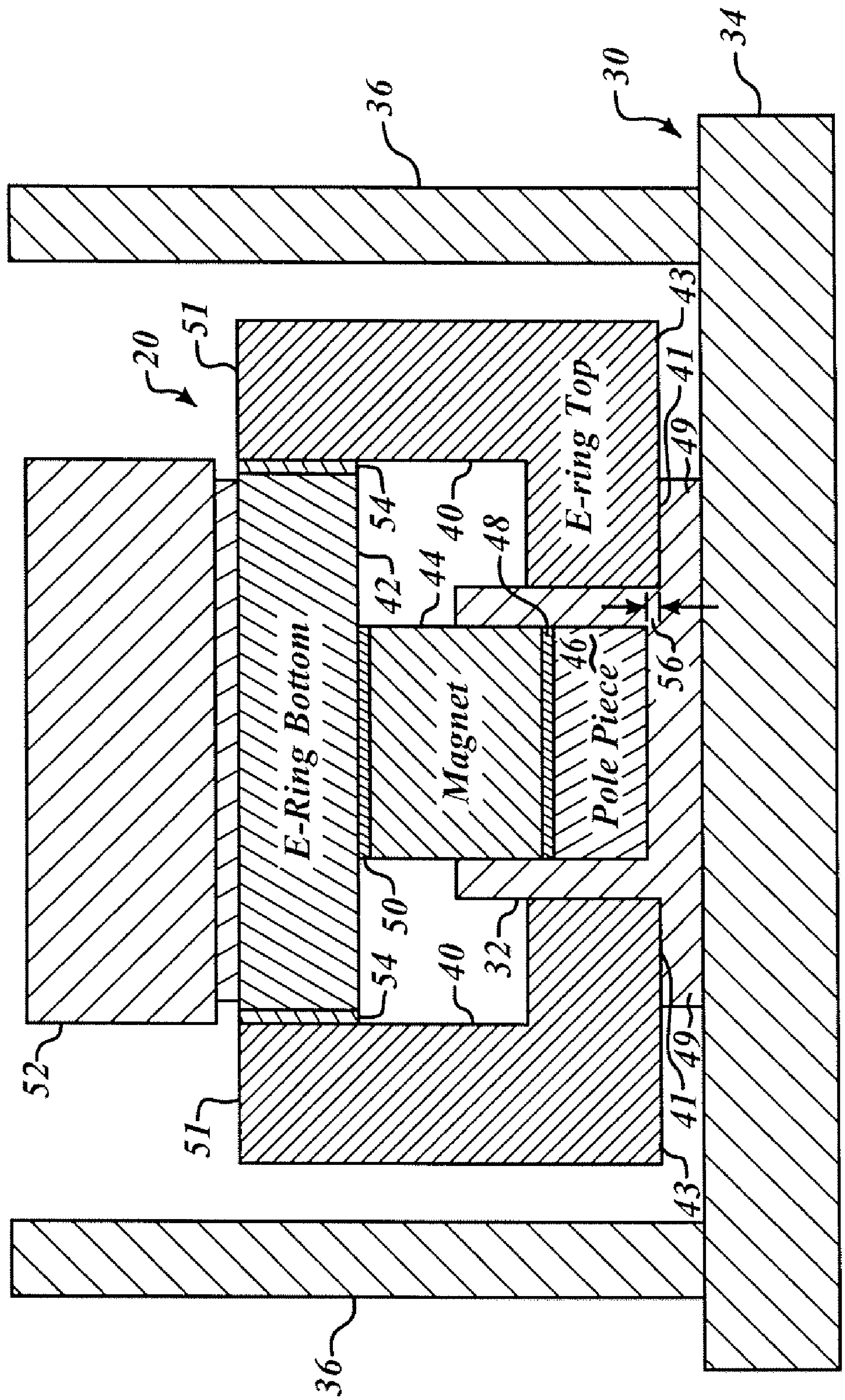

34
30
36
43
41
49
51
20
E-ring Top
54
40
48
42
44
56
46
Pole Piece
Magnet
E-Ring Bottom
50
54
40
32
49
41
43
51
52
36

FIG. 2

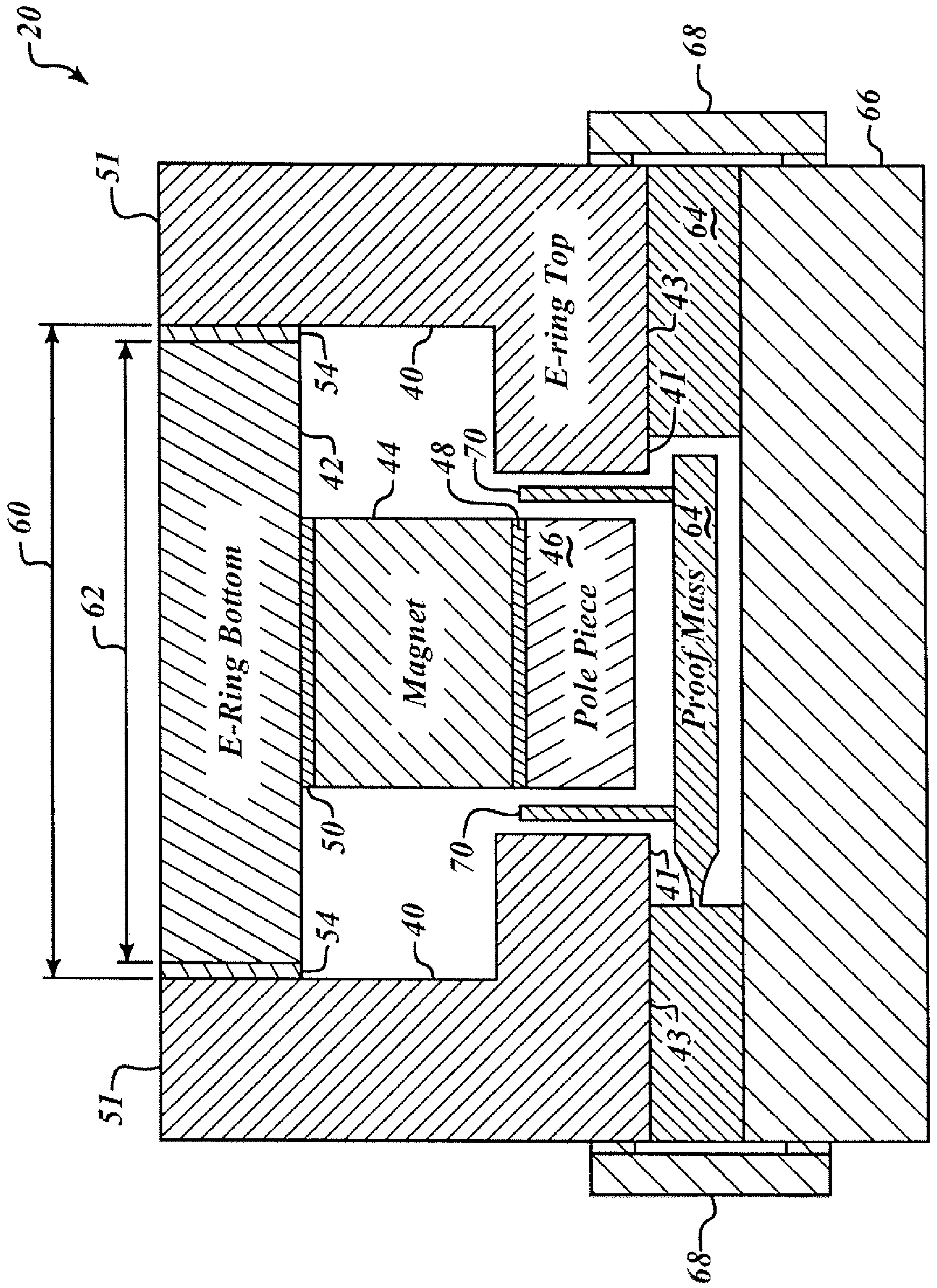

20
51
68
66
64
43
E-ring Top
40
41
54
42
44
48
70
60
62
46
64
E-Ring Bottom
Magnet
Pole Piece
Proof Mass
50
70
41
54
40
43
51
68

FIG.3

METHODS AND SYSTEMS FOR MINIMIZING VIBRATION RECTIFICATION ERROR IN MAGNETIC CIRCUIT ACCELEROMETERS

BACKGROUND OF THE INVENTION

Conventional magnetic return paths for accelerometers, such as the accelerometer shown in FIG. **1**, create a flux distribution in an air gap between an excitation ring and a pole piece that interacts with a coil that is attached to a flexible proof mass. The flux interacts with the current in the coil to produce a rebalance force proportional to the acceleration to which the device is subjected. The flux density across the air gap is not uniform given geometric constraints of constructing useful circuits. Further, the field strength of a magnetic circuit is not constant when it interacts with the coil with changing direction of current flow. The field strength follows the minor loop slope of the magnet. If the device is subjected to vibration which can change the orientation of the coil with respect to the flux and the amplitude of the flux itself, the output of the device will change independently of the acceleration being measured. This error is called vibration rectification error (VRE).

For any given magnetic circuit, there is an optimum location of the coil in the field to minimize VRE. Means have been developed to cope with this problem using spacers located between the coil and the proof mass. However, the spacers increase the pendulosity, add cost and increase the difficulty of manufacturing. Also, the desire to minimize the output change under vibration has led to the development of short coils that need to be extremely clean and uniformly manufactured to avoid contact with the components that define the air gap.

Typical manufacturing techniques present difficulties in producing a highly finished yet clean excitation ring because excitation rings are generally produced as one piece units that are difficult to machine and clean on their inner surface. This can result in small particles remaining that can interfere with proper operation of the accelerometer. Additionally, previous manufacturing techniques including those that use two piece excitation rings have a number of sources of possible error in the geometric configuration of the pole piece and magnet in relation to the coil, upper surface of the excitation ring, and proof mass. Bonding layers between the pole piece and magnet and between the magnet and excitation ring as well as the height of the pole piece and the height of the magnet are variable and can result in variability in the position of the pole piece and magnet between different accelerometers that results in increased vibration rectification error because the pole piece is not in an optimal position in relation to the other parts of the accelerometer.

SUMMARY OF THE INVENTION

The present invention includes systems and methods for minimizing vibration rectification error in magnetic circuit accelerometers. An example system is an accelerometer with an excitation ring that has a top piece with a lower portion inner diameter and a bottom piece having a diameter smaller than the lower portion inner diameter of the top piece. The accelerometer also includes a proof mass, a magnet mounted to the bottom piece of the excitation ring, a pole piece mounted to the magnet, and a coil attached to the proof mass that extends into a gap between the top piece of the excitation ring and the pole piece.

In accordance with further aspects of the invention, the bottom piece has a diameter approximately 3 mils smaller than the lower portion inner diameter of the top piece.

In accordance with other aspects of the invention, the pole piece is mounted to the magnet using a conductive epoxy and the magnet is mounted to the bottom piece using a conductive epoxy.

In accordance with still further aspects of the invention, the accelerometer also includes a stator mounted to the proof mass.

In accordance with yet other aspects of the invention, the accelerometer includes a bellyband attached to the excitation ring top piece and the stator such that the excitation ring top piece, the proof mass, and the stator are held in a fixed relationship to each other by the bellyband.

In accordance with additional aspects of the invention, the excitation ring top piece has an L-shaped cross-section.

In accordance with still another aspect of the invention, the methods include placing a pole piece in a pole piece to lap surface fixture, placing an excitation ring top piece on an outer portion of the pole piece to lap surface fixture, and placing an excitation ring bottom piece in a lower portion of the excitation ring top piece.

In accordance with still further aspects of the invention, the methods include applying a first adhesive layer to the pole piece, placing a magnet on the first adhesive layer, and applying a second adhesive layer to the magnet such that when the excitation ring bottom piece is placed in the lower portion of the excitation ring top piece, the excitation ring bottom piece is placed on the second adhesive layer.

In accordance with yet other aspects of the invention, the methods include using a conductive epoxy for the first and second adhesive layers.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred and alternative embodiments of the present invention are described in detail below with reference to the following drawings:

FIG. **1** shows an accelerometer formed in accordance with the prior art;

FIG. **2** is a cross-sectional diagram of a portion of an accelerometer being assembled using a tooling device; and

FIG. **3** is a cross-sectional diagram of an accelerometer formed in accordance with an example of the invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **2** is a cross-sectional diagram of a portion of an accelerometer **20** being assembled using a tooling device **30**. In the example shown, the tooling device **30** includes a mounting structure that may be referred to as a pole piece to lap surface fixture **32** in some examples, a base **34**, and a sidewall **36**. The accelerometer **20** includes an excitation ring (E-ring) top piece **40** into which an excitation ring bottom piece **42** is positioned. The tooling device **30** provides for highly accurate alignment of the parts of the accelerometer **20**. The E-ring top piece **40** includes a lap surface **41** at a first end **43** of the E-ring top piece **40**.

A magnet **44** is mounted to the E-ring bottom piece **42** and a pole piece **46** is mounted to the magnet **44**. The magnet **44** and pole piece **46** extend upward away from the E-ring bottom piece **42** toward a gap in the E-ring top piece **40**. The accelerometer **20** is shown upside down in FIG. **2**, so the magnet **44** and the pole piece **46** are shown extending downward away from the E-ring bottom piece **42**. The E-ring top piece **40** may also be referred to as an E-ring first piece and the

E-ring bottom piece **42** may also be referred to as an E-ring second piece in some examples.

In an example, the E-ring top piece **40** and bottom piece **42** are manufactured separately and heat treated. The E-ring top piece **40** is then rough lapped to a predefined finish quality on at least one surface. In an example, a lapped finish is applied to the lap surface **41** and the E-ring top piece **40** is then cleaned of residual particulate from the lapping operation. The E-ring bottom piece **42**, magnet **44**, and pole piece **46** are air abraded, and all parts including the E-ring top piece **40**, the bottom piece **42**, the magnet **44**, and the pole piece **46** are cleaned. Then, the accelerometer **20** is assembled. In an example, assembly of the accelerometer **20** is performed using a clean bench, which is an assembly bench that has a laminar stream of air flowing over the bench that has had airborne particles removed from the air, such as by using HEPA filters.

In an example assembly process, the pole piece **46** is placed in the pole piece to lap surface fixture **32**. Then, a first silver filled conductive epoxy layer **48** (e.g. Ablebond® 84-1LMIT produced by Ablestik Laboratories) is applied to the pole piece **46**. Next, the magnet **44** is attached to the pole piece **46** by placing the magnet **44** in the pole piece to lap surface fixture **32** on the first epoxy layer **48**. Then, a second silver filled conductive epoxy layer **50** (e.g. Ablebond® 84-1LMIT produced by Ablestik Laboratories) is applied to the magnet **44**. Next, the E-ring top piece **40** is placed in the tooling device **30** on an outer portion **49** of the pole piece to lap surface fixture **32**. Then, the E-ring bottom piece **42** is placed inside a second end **51** of the E-ring top piece **40** on the epoxy layer **50**. Then, a loading device **52**, such as a weight or spring for example, is used to apply a force to the E-ring bottom piece **42** to press a stack that includes the E-ring bottom piece **42**, the magnet **44**, and the pole piece **46** against the pole piece to lap surface fixture **32**. In an example, the loading device **52** applies pressure to the E-ring bottom piece **42** equivalent to that provided by a weight of at least **200** grams. Next, an unfilled, low viscosity epoxy layer **54** (e.g. TRA-BOND 931-1 produced by TRA-CON, Inc.) is applied between the E-ring bottom piece **42** and E-ring top piece **40**. An epoxy or other adhesive other than TRA-BOND 931-1 may be used. Such an alternative epoxy would typically have a low viscosity so that it effectively wicks into a gap between the E-ring top piece **40** and the E-ring bottom piece **41**. Such an alternative epoxy would also typically have a bond strength that will hold the E-ring top piece **40** and E-ring bottom piece **42** together and provide geometric stability over time to maintain the same flux level in the magnetic circuit. Application of the epoxy layer **54** may be performed by wicking the epoxy layer **54** into a gap between the E-ring top piece **40** and the E-ring bottom piece **42**, for example. The epoxy layers **48**, **50**, and **54** are then cured such as by heating for approximately 1 hour at 150 degrees Celsius for example. Although the epoxy layers **48**, **50**, **54** are cured at the same time in this example, they may be cured sequentially or under different conditions in other examples.

Use of the pole piece to lap surface fixture **32** in assembly of the accelerometer **20** results in a pole piece to lap surface distance **56** that may be controlled to high tolerances by controlling the dimensions of the pole piece to lap surface fixture **32**. This results in the pole piece to lap surface distance **56** being consistent between different accelerometers manufactured in this way and allows the pole piece to lap surface distance **56** to be controlled without undue concern about variability in the magnet **44** height, the pole piece **46** height, the thickness of the first epoxy layer **48**, and the thickness of the second epoxy layer **50**. The tooling device **30** is then removed and additional components are added to the accelerometer **20** to produce the structure shown in FIG. **3**. FIGS. **2** and **3** are not necessarily drawn to scale. Although FIGS. **2** and **3** show various parts of the accelerometer **20** in cross-sectional views, it should be understood that the parts have a volume. In an example embodiment, the E-ring top piece **40** and the E-ring bottom piece **42** are cylindrical. In some examples, other components such at the magnet **44** and the pole piece **46** may also be cylindrical in shape.

FIG. **3** is a cross-sectional diagram of the accelerometer **20** shown in FIG. **2** after the tooling device **30** has been removed and additional components have been added. FIG. **3** also shows that the E-ring top piece **40** includes a lower portion inner diameter **60** at the second end **51** that is greater than a diameter **62** of the E-ring bottom piece **42**. This allows the E-ring bottom piece **42** to slide into the E-ring top piece **40** during the assembly described with respect to FIG. **2**. In an example, the lower portion inner diameter **60** is 0.75±0.001 inches and the diameter **62** is 0.747±0.001 inches resulting in a difference in diameter of 0.003±0.002 inches (3±2 mils or a difference in diameter between 1 and 5 mils). In an example, the E-ring bottom piece **42** has a diameter approximately 3 mils smaller than the lower portion inner diameter of the E-ring top piece **40**. Although the E-ring top piece **40** has an L-shaped cross-section in this example, the E-ring top piece **40** may have other cross-sectional profiles in other examples such as a generally L-shaped profile with one or more rounded corners. Additionally, other sized configurations can be used provided the diameter **62** of the E-ring bottom piece **42** is smaller than the lower portion inner diameter **60** of the E-ring top piece **40**.

After the tooling device **30** is removed, a proof mass **64** is added on top of the E-ring top piece **40** and a stator **66** including accelerometer electronics is mounted to a fixed portion of the proof mass **64**. Then, the proof mass **64** and stator **66** are held in place in relation to the E-ring top piece **40** such as by using a bellyband **68** for example. It should be understood that it is an outer rigid portion of the proof mass **64** that is held in place in relation to the E-ring top piece **40** and that other portions of the proof mass **64** will flex during operation of the accelerometer **20**. A coil **70** is also shown extending from the proof mass **64** into a gap between the pole piece **46** and the E-ring top piece **40**. In an example, the lap surface **41** also functions as a ground plate of a capacitor formed between the lap surface **41** and a metallized plate (not shown) on the proof mass **64**. A mirror image version of the accelerometer portion of FIG. **2** can also be created and attached to a second side of the proof mass **64** to increase common-mode cancellation of stresses and magnetic behavior over a predefined temperature range. Some or all assembly of the accelerometer **20** may be performed in a clean room in some examples.

While the preferred embodiment of the invention has been illustrated and described, as noted above, many changes can be made without departing from the spirit and scope of the invention. For example, other types of epoxy or types of adhesive other than epoxy may be used and methods of mounting and attachment other than the use of adhesives may be used in some examples. Additionally, although a single sided accelerometer is described, double sided accelerometers may also be formed using similar two piece excitation rings in some examples. Other types of tooling devices that use the pole piece to lap surface fixture **32** may also be used in some examples. Differing step orders in assembling the accelerometer **20** may be followed in some examples and/or some parts may be preassembled before combining with other parts such as by attaching the magnet **44** to the pole piece **46** before insertion into the pole piece to lap surface fixture **32** for example. Accordingly, the scope of the invention is not limited by the disclosure of the preferred embodiment. Instead, the invention should be determined entirely by reference to the claims that follow.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An accelerometer comprising:
a proof mass;
at least one excitation ring comprising:
a first piece having a first inner diameter at a first end and a second inner diameter at a second end; and
a second piece having a third diameter,
wherein the third diameter is smaller than the second inner diameter;
at least one magnet mounted to the second piece of the excitation ring;
at least one pole piece mounted to the at least one magnet; and
at least one coil attached to the proof mass,
wherein the first piece of the excitation ring is adjacent to the pole piece across a gap at the first end of the first piece and wherein the coil extends into the gap.

2. The accelerometer of claim **1**, wherein the third diameter is between 1 and 5 mils smaller than the second inner diameter of the first piece.

3. The accelerometer of claim **2**, wherein the third diameter is approximately 3 mils smaller than the second inner diameter of the first piece.

4. The accelerometer of claim **1**, wherein the at least one pole piece is mounted to the at least one magnet using a conductive epoxy.

5. The accelerometer of claim **4**, wherein the at least one magnet is mounted to the second piece of the excitation ring using a conductive epoxy.

6. The accelerometer of claim **5**, wherein the second piece is mounted to the first piece using epoxy.

7. The accelerometer of claim **1**, further comprising a stator mounted to a fixed portion of the proof mass, wherein the stator includes accelerometer electronics.

8. The accelerometer of claim **7**, further comprising a bellyband attached to the excitation ring first piece and the stator such that the excitation ring first piece, the proof mass, and the stator are held in a fixed relationship to each other by the bellyband.

9. The accelerometer of claim **1**, wherein the excitation ring first piece has an L-shaped cross-section.

10. The accelerometer of claim **1**, wherein the third diameter is larger than a diameter of the pole piece.

11. A method of aligning components of an accelerometer, the method comprising:
aligning a magnet and pole piece component with a first piece of an excitation ring using a mounting structure; and
attaching an excitation ring second piece to the excitation ring first piece and to the magnet and pole piece component
wherein aligning the magnet and pole piece component with the first piece of the excitation ring comprises placing a first end of the excitation ring first piece on an outer portion of the mounting structure.

12. The method of claim **11**, wherein the mounting structure provides an accurate spacing between the magnet and pole piece component and the first piece as well as a gap for a coil.

13. The method of claim **11**, wherein aligning the magnet and pole piece component with the first piece of the excitation ring comprises:
placing a pole piece in the mounting structure;
applying a first adhesive layer to the pole piece; and
attaching a magnet to the first adhesive layer.

14. The method of claim **13**, wherein attaching the excitation ring second piece to the first excitation ring piece and to the magnet and pole piece component comprises:
applying a second adhesive layer to the magnet;
placing the excitation ring second piece on the second adhesive layer;
applying a force to the excitation ring second piece to press a stack that includes the excitation ring second piece, the magnet, and the pole piece against the mounting structure; and
applying a third adhesive layer between the excitation ring second piece and the excitation ring first piece.

15. The method of claim **14**, wherein the first adhesive layer is a conductive epoxy and the second adhesive layer is a conductive epoxy.

16. The method of claim **14**, wherein the third adhesive layer is an unfilled, low viscosity epoxy.

17. The method of claim **14**, further comprising curing the first, second, and third adhesive layers.

18. The method of claim **17**, wherein curing is performed for approximately 1 hour at approximately 150 degrees Celsius.

19. The method of claim **14**, further comprising:
removing the mounting structure;
attaching a proof mass with a coil to the excitation ring first piece; and
attaching a stator to the proof mass.

20. The method of claim **19**, further comprising attaching a bellyband to the excitation ring first piece and the stator such that the excitation ring first piece, the proof mass, and the stator are held in a fixed relationship to each other.

* * * * *